NASA CONTRACTOR REPORT

NASA CR-1233

NASA CR-1233

A LUNAR GRAVITY SIMULATOR

VOLUME I

Prepared by
CASE WESTERN RESERVE UNIVERSITY
Cleveland, Ohio
for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1968

NASA CR-1233

A LUNAR GRAVITY SIMULATOR

VOLUME I

Prepared under Contract No. NAS 1-7459 by
CASE WESTERN RESERVE UNIVERSITY
Cleveland, Ohio

for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

This report, in three volumes, describes a prototype lunar gravity simulator using novel magnetic air bearing supports with Negator® spring motors and especially designed harness. The work was done under NASA Contract NAS1-7459 by the Engineering Design Center, Case Western Reserve University; Industrial Design Department, Cleveland Institute of Art; and John L. Fuller and Associates, all of Cleveland, Ohio. The system built for National Aeronautics and Space Administration, Langley Research Center, Langley Station, Hampton, Virginia, is based on preliminary work done by two graduate students at Case Western Reserve University (Richard Morgen and Dennis Millett) and students at the Industrial Design Department of the Cleveland Institute of Art (Norman Yates and Michael Ault).

Following feasibility tests and two master's theses covering the magnetic air bearings and the use of Negator® springs*, the present development was undertaken in collaboration with John L. Fuller and Associates who undertook to design and build a complete prototype system.

2.0 SIMULATOR SYSTEM

The prototype lunar gravity simulator is depicted schematically in Figure 1. The system is suspended from a temporary 4 ft. by 6 ft. steel ceiling. A "shirtsleeved" subject in crash helmet and boots rides in a three-axis gimbaled harness system as shown. The harness system is suspended from the center of an aluminum spider ring which, in turn, is supported at its perimeter by from four to six nylon-coated steel cables that wind and unwind from constant force spring motors

---

* Product of Hunter Spring Co., Hatfield, Pennsylvania

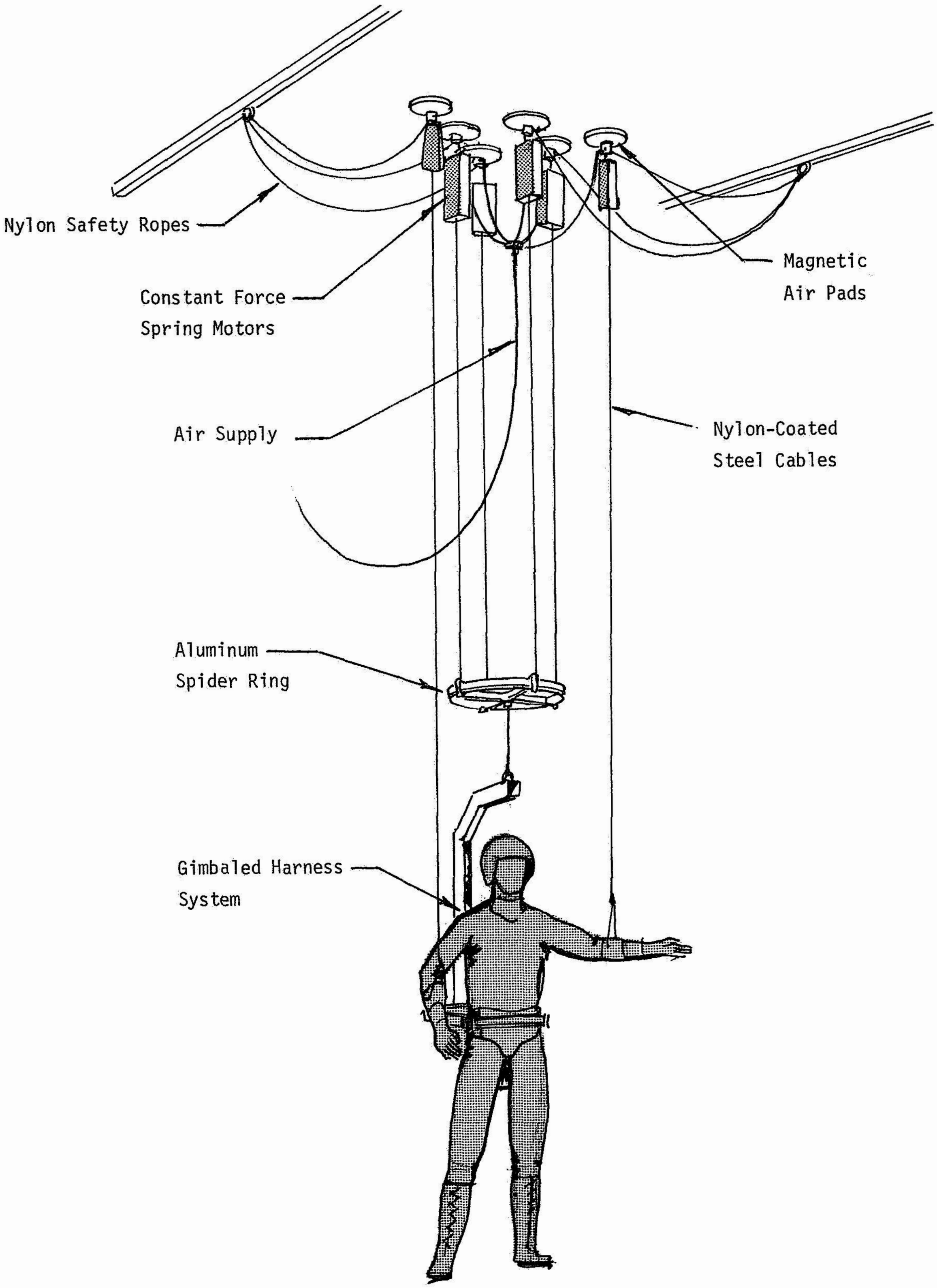

Figure 1 Prototype Lunar Gravity Simulator

that are close to the ceiling and are joined to it through floating magnetic air pads. Nylon ropes attached between each of the constant force motors and the edge of the ceiling prevent the motors from falling on the subject if the magnetic air pads break loose from the ceiling.

The system permits the subject to remain in the vertical position with approximately 5/6 of his weight supported by the constant force spring motors. Two smaller constant force spring motors support each of the arms independently. The weight of the legs are negated by spring motors mounted on the gimbal suspension system. The subject may rotate about a vertical axis indefinitely, pitch forward to a horizontal position, pitch backward to 15 degrees, and roll to a horizontal position on either side. He may move his legs fore and aft or to the sides. The magnetic air bearings permit motion fore and aft and to each side as well as rotation with virtually no frictional restraint. The relatively light weight of the magnetic air bearings and the Negator® spring motors minimizes inertial reactions on the moving subject. Test subjects have remained in the simulator for several hours without discomfort.

2.1 Specifications

The simulator is designed to accommodate subject weights from approximately 168 pounds to 264 pounds. Three different subject weights can be accommodated by changing the number of constant force motors supporting the harness ring from 4 to 5 and from 5 to 6, respectively. Each of the constant force motors supplies a lifting force of approximately 40 pounds as delivered. The harness and gimbal system weighs approximately 33 pounds. Accordingly, the 4-motor support configuration negates a subject weight of 168 pounds, a 5-motor support configuration supports a subject weight of 216 pounds, and the 6-motor configuration negates 264 pounds of subject weight. Intermediate subject weights can be negated by adding weights to the support ring or by changing the cable-drums on the constant force motors so that the motors produce a lower output force. Cable drums of different diameters have not been supplied with the prototype simulator but can be furnished by John L. Fuller and Associates.

Because standard B-motor® spring units* were used in each of the principal constant force motors, the range of travel for the simulator is substantially extended over what it was for the pre-prototype unit which employed Negator® springs. The simulator, with the ceiling supported approximately 13 ft. 8 in. above the floor on which the subject stands, permits a vertical range of travel of approximately 6 feet for the torso and approximately 9 feet of travel for the arms of the subject. John L. Fuller Drawing No. 1333C15 (available upon request) depicts the height relationships of the simulator.

2.2 Testing

The simulator was subjected to extensive testing by several subjects. These tests determined that: (a) the simulator is structurally sound; (b) the dynamic response of the simulator minimizes distortion of the simulation of a lunar gravity condition; (c) the simulator may be used for a wide range of experiments as described later in this report; (d) the safety provisions of the simulator function as designed to protect the subject.

---

* Designation of Hunter Spring Co. for dual coil back-wound Negator® spring assemblies.

2.3 Precautions Regarding Operation

In making use of the simulator, several precautionary points about its operation should be observed as follows:

1. The weight supporting spring motors should not be permitted to retract freely to the positive stop from an extended position. Over-running of the spring may occur with attendant permanent deflection.

2. The safety-line system must be securely attached to the motors to prevent injury to personnel and damage to equipment in the event that magnet pads break loose from the ceiling.

3. The steel ceiling surface must be maintained smooth and free from obstructions that would tend to break down air film between the magnetic air pads and the ceiling surface.

4. Bumpers on the spring motor cables should not be permitted to make contact with the stops on the motor frames during a jump maneuver; one foot minimum clearance from the stop should be maintained.

5. Inner leg motors should not be extended by hand. Extension distance is limited; springs will come off drums if over-extended with attendant potential damage to springs.

3.0 MAJOR SUBSYSTEMS

3.1 Body Harness

The purpose of the body harness and support assembly is to hold the test subject firmly and comfortably in the simulator and to apply the negation force to the torso and limbs. The body harness assembly is shown in John L. Fuller Drawing No. 1333J1 (available upon request). The three degrees of freedom (see Figure 2) provided by the body harness are restricted in the following ways. Rotation around the subject's Y axis (pitch) is limited to slightly more than 90 degrees

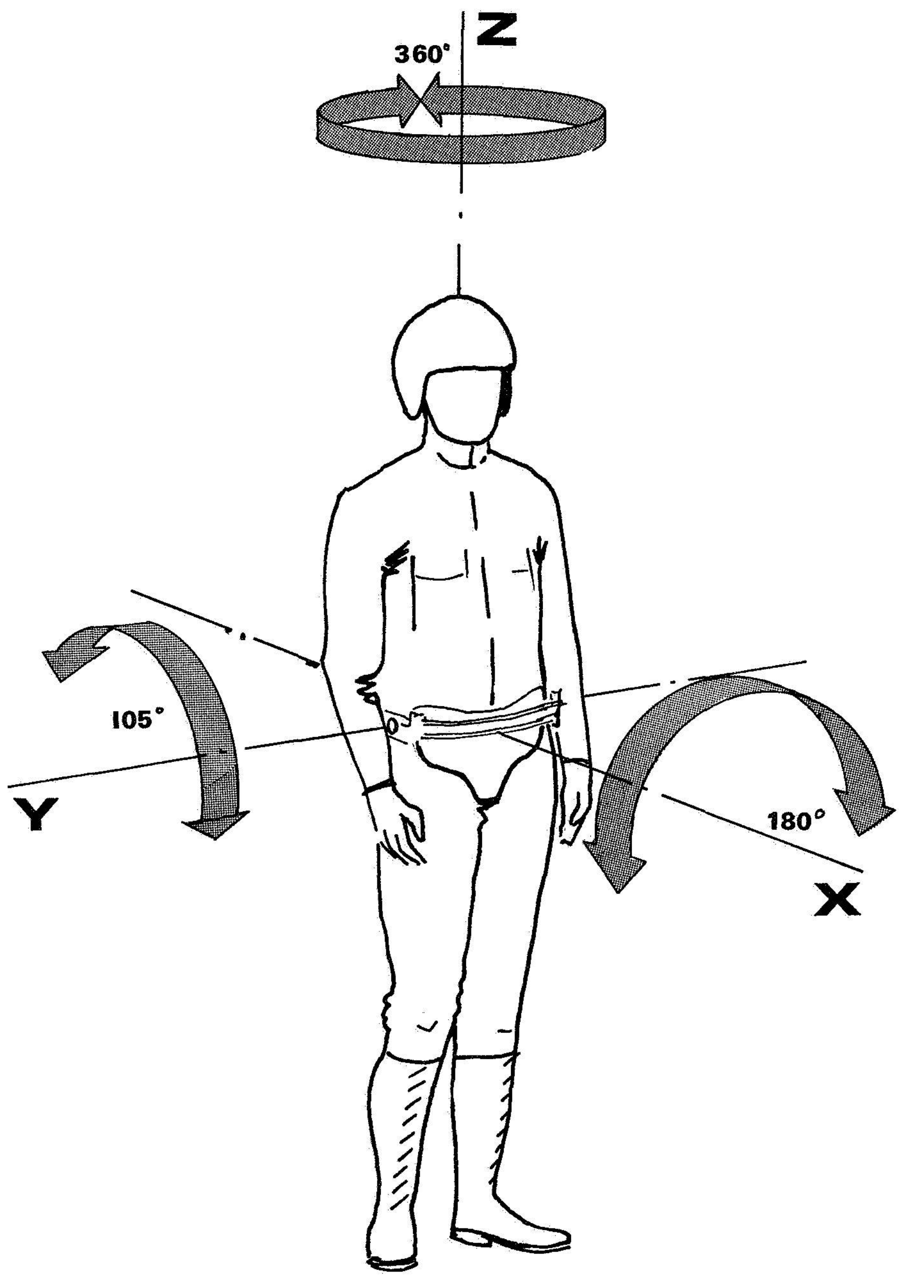

Figure 2 Range of Motion - Harness and Gimbal System

forward rotation and approximately 15 degrees rearward. Rotation around the subject's X axis (roll) is 90 degrees either side of the vertical. Rotation around the subject's Z axis (yaw) is 360 degrees.

The body segment weights were grouped as follows for negation purposes in order to provide the most comfortable and unrestricted subject movement. The torso, head, 2/3 of the weight of the upper arms, and full weight of the legs were negated as a unit (torso unit). One-third of the upper arm, the lower arm, and hand were negated as a unit as was 1/3 of the weight of the upper leg, the lower leg, and the foot.

The weights of the body segments of a 216 pound man (total clothed weight) which were used for design purposes are as follows:

Head	Torso	Upper Arm	Lower Arm
15.1	105.6	7.0	4.1
Hand	**Upper Leg**	**Lower Leg**	**Foot**
1.4	21.6	10.8	3.1

The corresponding weights of segment groupings (216 pound suited man) are as follows:

Torso Unit	Lbs.	Leg Unit (ea.)	Lbs.	Arm Unit (ea.)	Lbs.
Torso	105.0	1/3 Upper Leg	7.2	1/3 Upper Arm	2.3
Head	15.1	Lower Leg	10.7	Lower Arm	4.1
2/3 Upper Arms	9.3	Foot	3.1	Hand	1.4
Legs	70.6		21.0		7.8
	200.0				

Negation Forces:

				Motors Required
Torso Unit	- 5/6 of 200.0	=	167.0 lbs.	
Torso Unit plus 33 lb. rig		=	200.0 lbs.	5 at 40 lbs.
Leg Unit	- 5/6 of 21.0	=	17.5 lbs.	1 each at 15 lbs.
Arm Unit	- 5/6 of 7.8	=	6.5 lbs.	1 each at 15 lbs.

The body harness is comprised of the following elements: Torso Harness, and pivoted "C" and "L" frames, Leg Harness, and Arm Harness.

3.2 Torso Harness

The harness for supporting the torso consists of an aluminum frame, spring and foam seat (bicycle style), and a rigid fiber glass shell and foam pad which conforms to the front of the pelvic area of the torso. The torso unit is mainly supported on the ischial tuberosities of the pelvis and also against the iliac crests of the pelvis. The subject is held in the harness by a strap which goes around his hips and fastens at his back.

The seat and pelvic support pieces are adjustable (see Figure 3) in relationship to each other and to the Y axis pivot points of the harness which are located at the sides of the assembly. The adjustments allow up and down and fore and aft positioning of the subject in the harness so that his body center of gravity, when in an erect position, will coincide with the Y axis pivot points of the harness.

In the tests run on the prototype it was found that generally each subject required a different seat-to-pelvic support relationship for comfort. This was achieved for each subject by moving the pelvic support in and out. It was found that this adjustment did not appreciably change the relationship of the center of gravity of different subjects and the Y axis pivot points. This latter relationship was established by positioning the seat experimentally until the subject, when lifted off the floor in the harness and tilted forward in an erect posture, would remain in the tilted position.

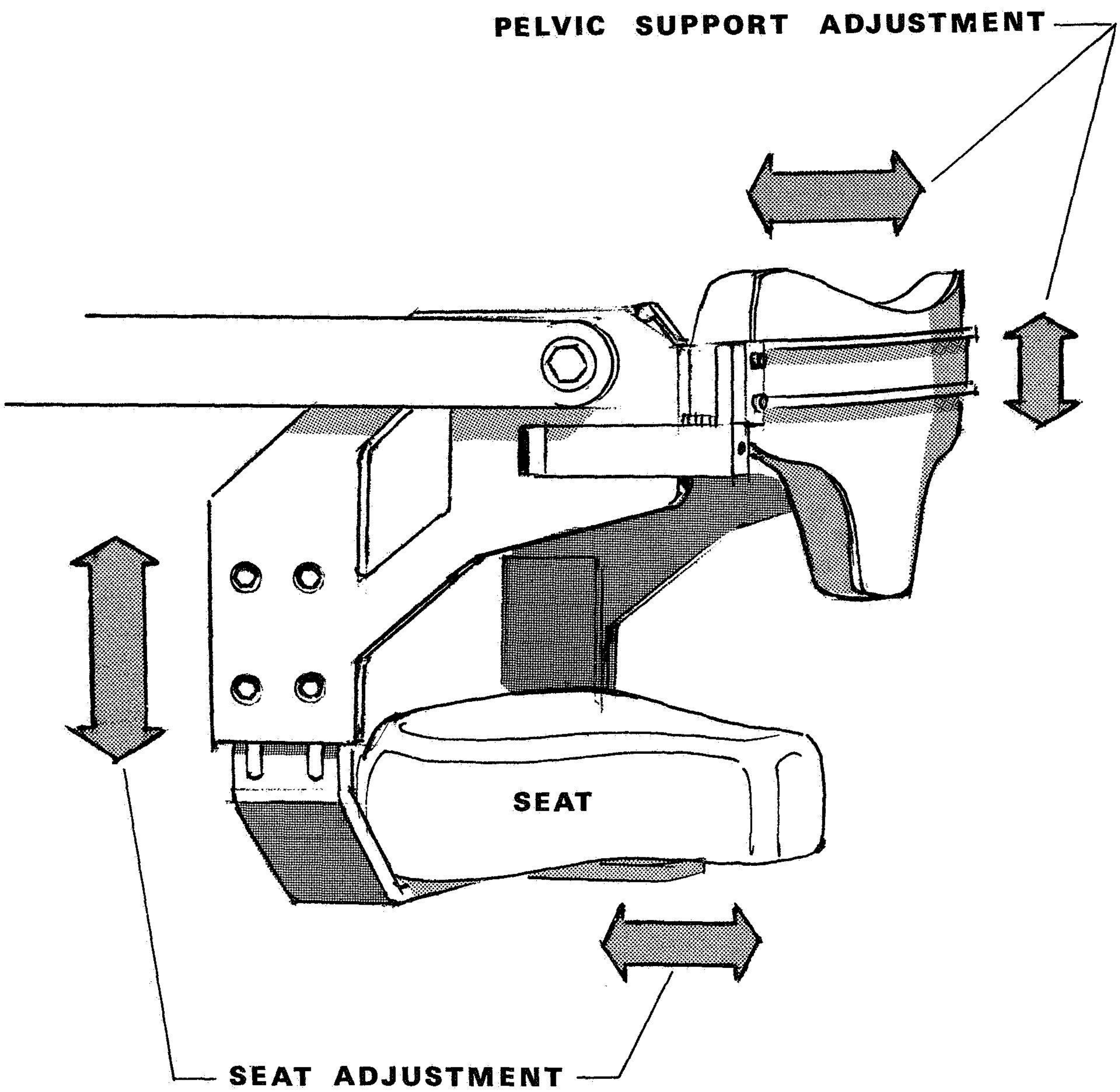

Figure 3 Torso Harness Adjustments

The pelvic support is a separate piece and is held to the harness frame by sliding rack. Finger-operated latches for the racks make ingress and egress from the harness unit a relatively simple procedure.

A number of tests with various subjects were conducted to verify comfort levels of the torso harness. The subjects remained in the simulator from two to four hours each and generally all reported an awareness of some discomfort (pressure on the muscle areas in contact with the seat) after the first half hour. The level of discomfort experienced, however, did not in any case reach the threshold levels of actual pain. No after-effects were reported in any instance of declared discomfort. It should be noted that all the tests were run in a situation which did not permit natural walking or running movements; these could only be approximated. It was further found that if the subject was involved in some activity other than specifically concentrating on his discomfort level (i.e., simulated walking, etc.) awareness of discomfort disappeared.

The torso harness is held in a C-shaped aluminum frame extending around the back of the subject with bearing pivots in the "C-frame" that permit the subject to rotate 105 degrees around his Y axis. This "C-frame" is in turn attached at its back center to a bearing pivot which lies on the X axis of the torso permitting 180 degrees-plus rotation of the subject around his X axis.

The X axis pivot is attached to the bottom of an aluminum frame shaped like an inverted "L", which hangs at an angle such that its upper end, where it is connected to the overhead Negators® is above the subject's center of gravity. This plus the easy compliance of the frictionless overhead air pads, permits the subject to rotate 360 degrees around his vertical (Z) axis.

3.3 Leg Harness

Each leg of the subject (see Figure 4) is supported in a knee-high boot from which are attached inside and outside constant force motors.

One Negator® spring unit for each leg is fastened to the underside of the torso harness and is connected directly to the inside of the subject's boot.

A second constant force unit for each leg is fastened to the underside of the "C" brace and is connected to the outside of the subject's boot by means of a cable and a pulley. This arrangement of negation devices for the leg tends to balance the torque forces on the leg. The point of attachment of the negation cables to the boot was at the estimated center of gravity of the leg segment which consists of 1/3 of the weight of the upper leg, all of the weight of the lower leg, and the foot. In all tests run, leg-segment negation was considered comfortable by all subjects.

3.4 Arm Harness

Each arm of the subject (see Figure 5) is supported by a foam padded metal sling which is strapped to the arm with Velcro straps. The arm sling has a cable-loop running over a pulley which is, in turn, attached to a cable which goes to an overhead Negator® motor and magnetic air pad. The movement of the cable over this pulley

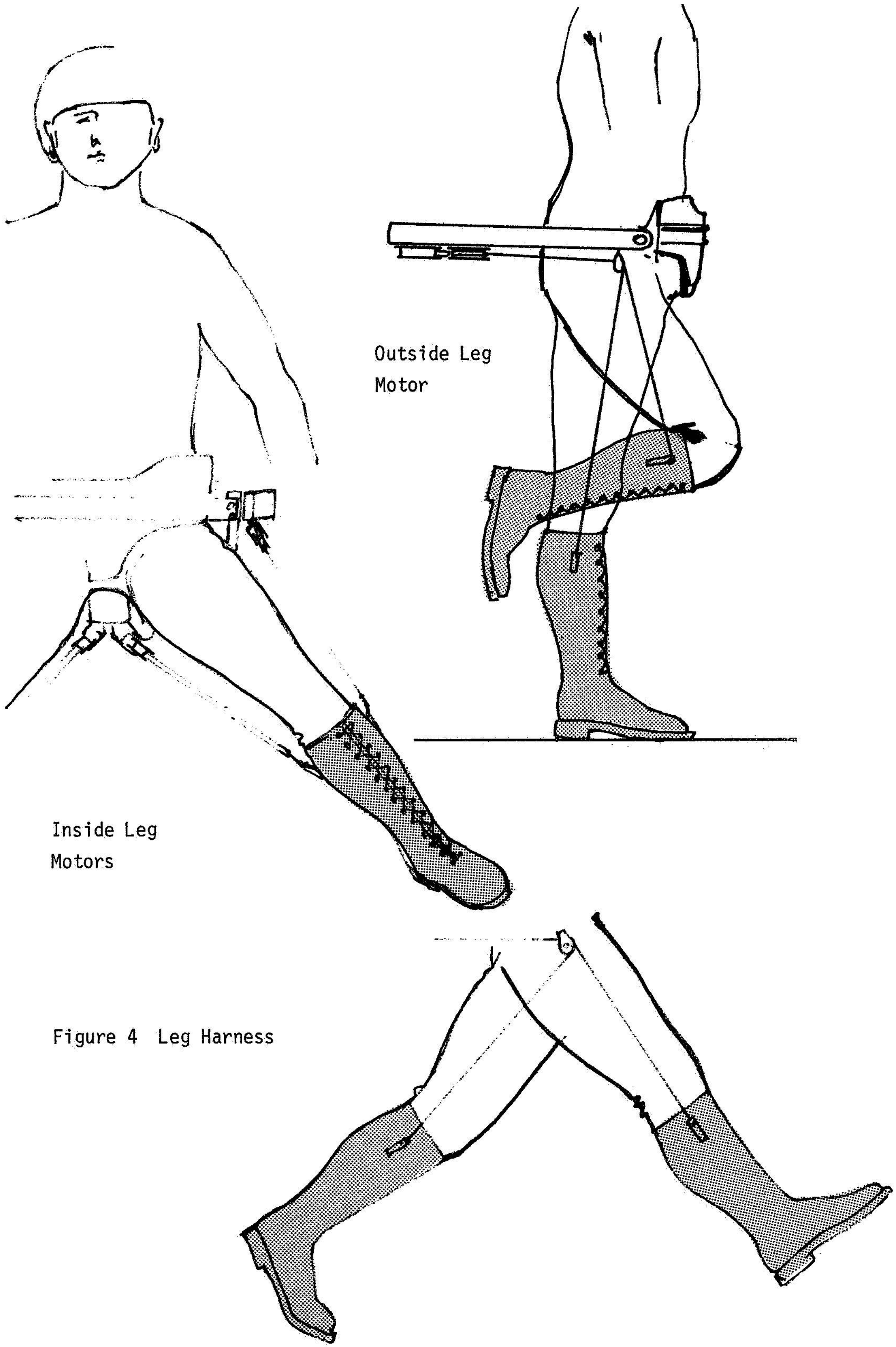

Figure 4 Leg Harness

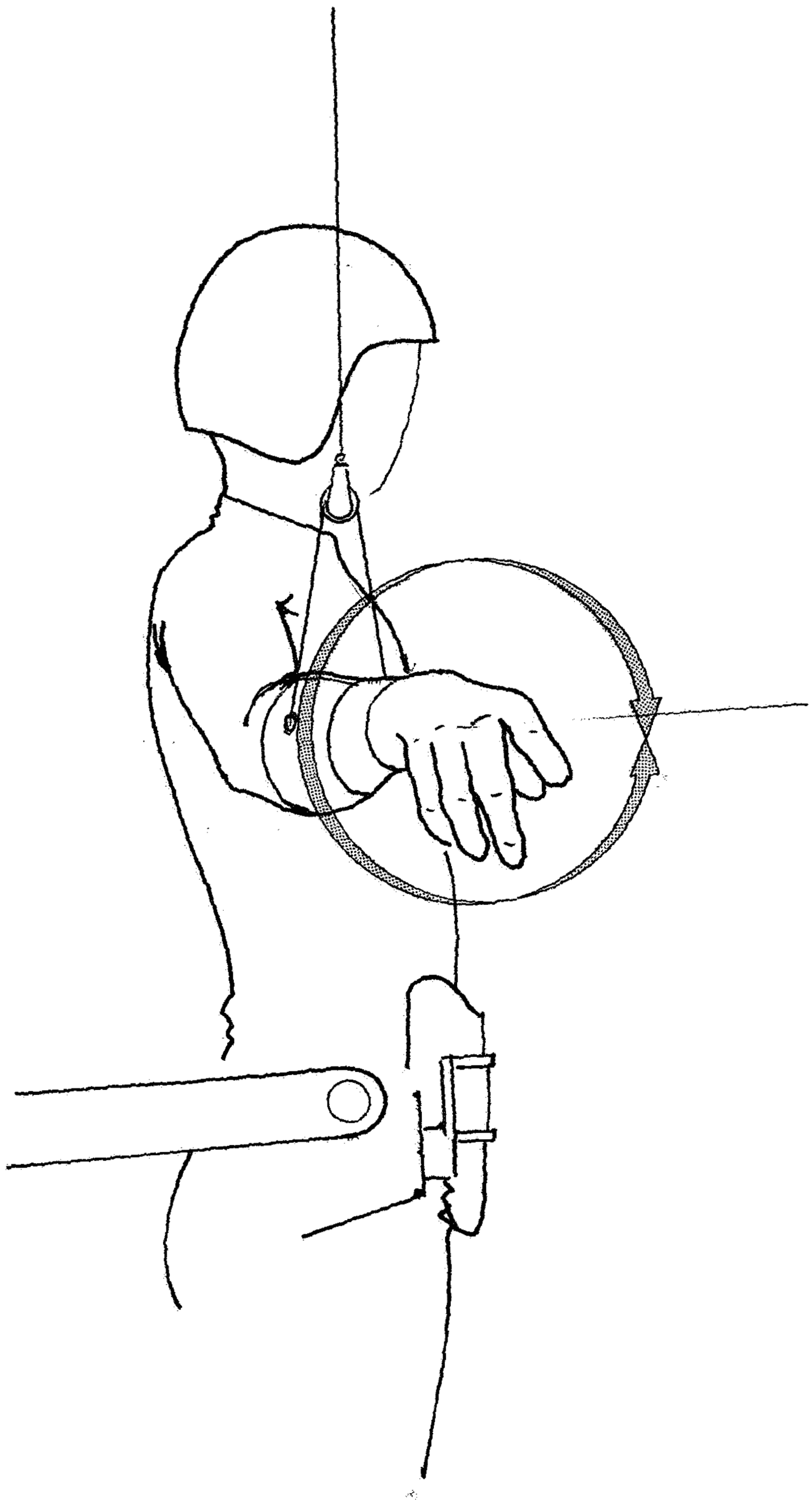

Figure 5 Arm Harness

allows the arm to rotate 270 degrees with no interference. The attachment of the arm sling to the arm is just below the elbow at the estimated center of gravity of the arm segment which consists of 1/3 of the weight of the upper arm, all of the weight of the lower arm, and the hand. In all tests run, arm segment negation was considered comfortable by all subjects.

3.5 Ingress and Egress Procedures

The following procedure was used during all testing of the simulator to get the subject in and out of the body harness:

1. Subject puts on boots and other test equipment.
2. Remove pelvic support and hold simulator down to a position approximately 6 inches below normal.
3. Subject backs into simulator and the pelvic support racks are inserted into slides on torso harness to desired position and locked.
4. Waist strap which is attached to pelvic support is fastened.
5. Leg Negators® are fastened to boots.
6. Arm negation slings are fastened to the subject's arms.

For egress, the above procedure is repeated but in reverse order. Care must be exercised in emergency egress situations to assure that the torso harness unit is held down as the subject leaves.

3.6 Constant Force Motors

Three types of motor assemblies are used on the lunar gravity simulator. Up to six motors with a nominal tension of 40 pounds each are used to support the frame, torso, and legs of the subject depending on his weight and extra gear. These are called "Main Motor Assemblies" and appear on John L. Fuller Drawing No. 1333D4. Two "Outer Leg Motor Assemblies" with nominal tension of 10 pounds each are shown in John L. Fuller Drawing No. 1333C12. Two "Inner Leg Motor Assemblies" with nominal tensions of 5-1/4 pounds each are shown in John L. Fuller Drawing No. 1333J1, and two "Arm Motor Assemblies" with nominal tension of 5 pounds each are shown in John L. Fuller Drawing No. 1333C13. All of these assembly drawings are available upon request. These motors are also shown in Figures 6 and 7.

The motors are designed to provide reasonably constant linear force through a 6 foot extension of the wire cables which wind around drums. Pairs of Negator® springs are "back-wound" to minimize variations in force and increase linearity. Detailed specifications for the spring motors themselves are given in the John L. Fuller parts list (available upon request). The design is intended to obtain more than 50,000 stress reversals from the Negator® springs. Figure 8 shows the amount of total hysteresis as measured on one Main Motor Assembly at various extensions. Force to start extension (from rest) is added to force to start retraction. Teflon power lubrication substantially lowered hysteresis as shown in Figure 8.

The design of these motors is based on the work done by master's candidate Richard Morgen who discusses details of their characteristics and who presents performance equations in his master's thesis entitled: "The Design of a Vertical Lunar Gravity Simulator", which is included in Volume II of this report as NASA CR-1234.

3.7 Magnetic Air Pads

Eight magnetic air pads have been made for use with the lunar gravity simulator. These air pads are intended to operate from a

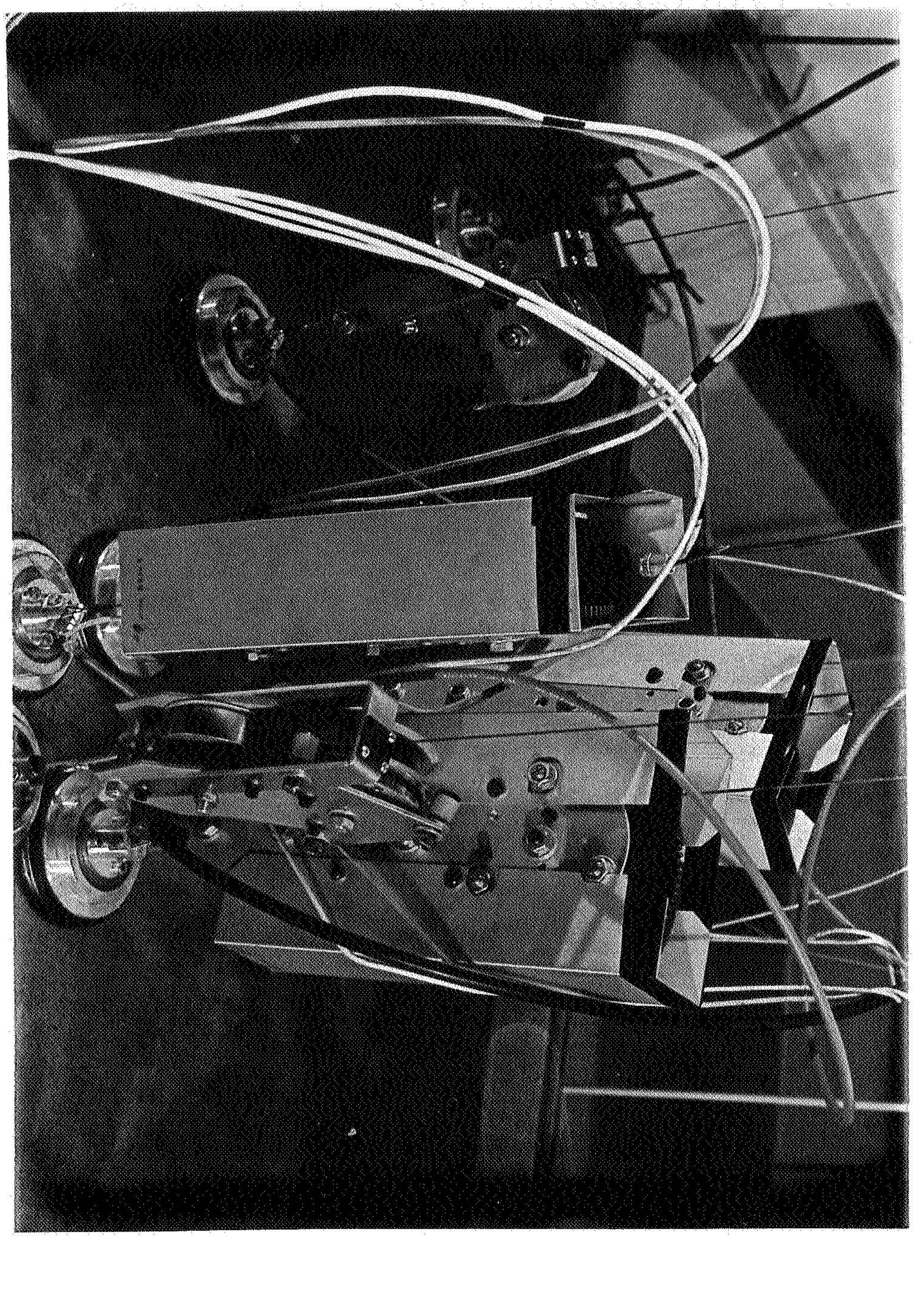

Figure 6 Photo of Main Support Motors

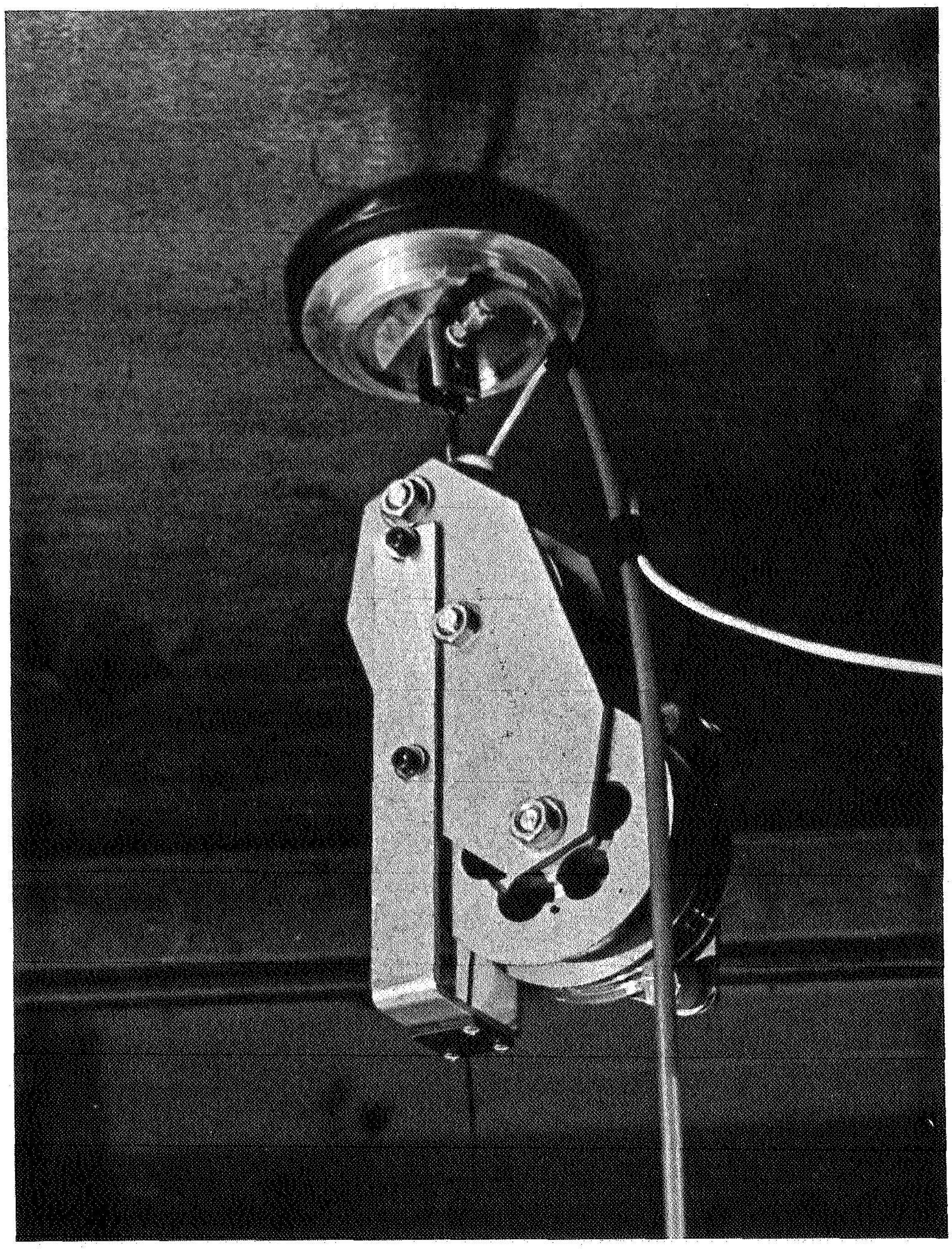

Figure 7 Photo of Arm Support Motors

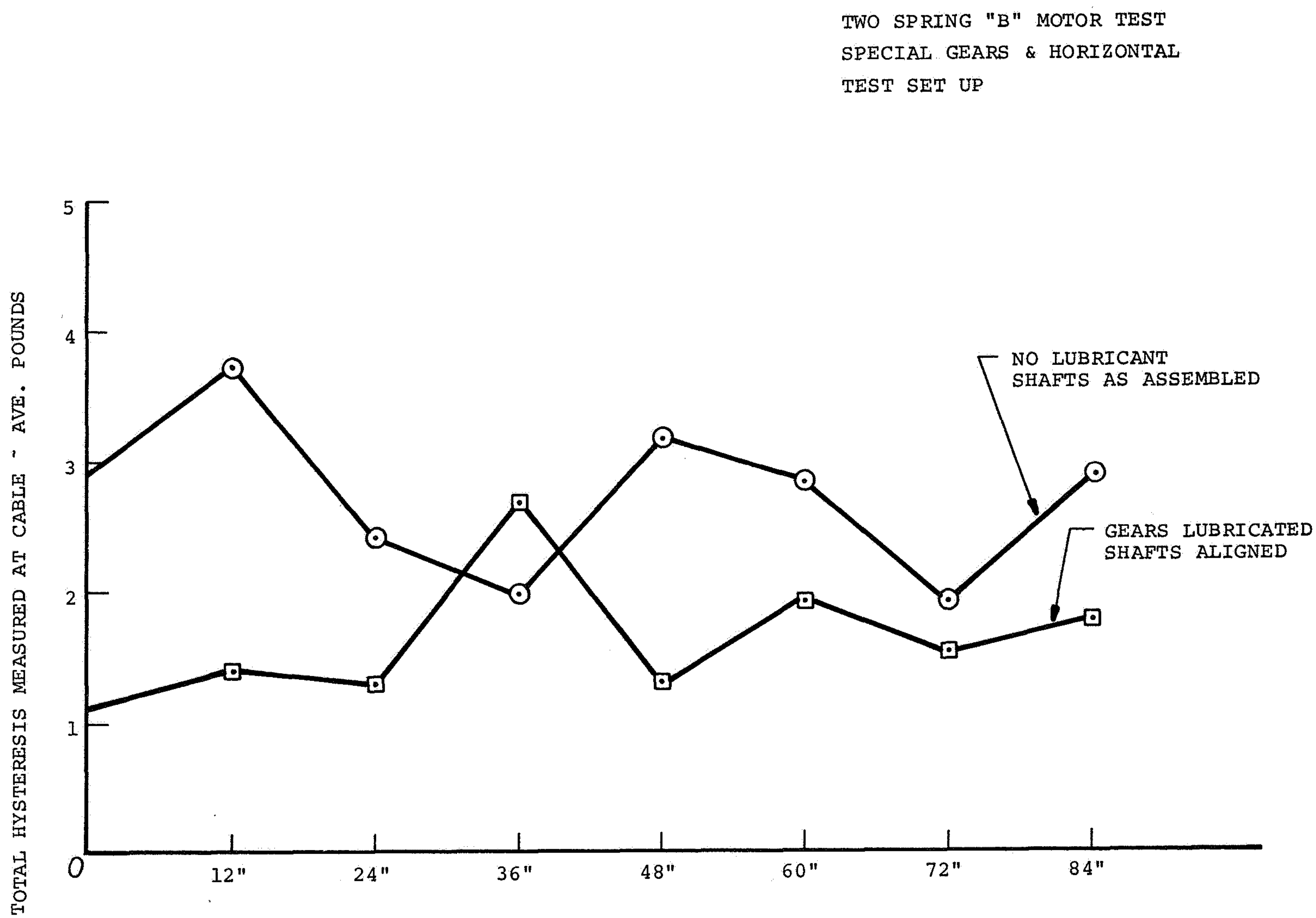

Figure 8 Typical Hysteresis in Main Motor

very smooth steel ceiling. The magnetic air pad assembly drawing is John L. Fuller Drawing No. 1333C17 (available upon request).

A powerful ceramic magnet is strongly attracted to the steel ceiling while, at the same time, being forced away from the ceiling by a continuous flow of air which is supplied from a central hole and which flows radially outward. With pull of the constant force spring air pad, it operates at an equilibrium position of 3 or 4 thousandths of an inch air gap from the ceiling. The characteristics are arranged so that the system acts like a very stiff spring over an extension of a few thousandths of an inch such that the force may be increased up to double its working load before the pad becomes unstable and pulls away from the ceiling. Under normal operating conditions, the magnetic air bearing is free to move laterally in any direction with virtually no friction. Details covering the theoretical design of the magnetic air pads are given in the master's thesis by Dennis Millett entitled: "The Design of a Magnetic Air Bearing for Use in a Lunar Gravity Simulator", which is included in Volume III of this report as NASA CR-1235.

The six magnetic air pads for use with the main motor assemblies have been magnetized to a level of 900 to 1000 gauss so that they will hold with a force of about 75 pounds when measured with a plastic film spacer which is 0.005 inches thick. The two arm air pad magnets are magnetized to a value of 800 gauss so that they hold to the force of 37 pounds when separated from a steel surface by a piece of plastic which has a thickness of 0.005 inches. Breakaway force as a function of magnetization level is presented in Figure 9. Breakaway force levels for each of the magnetic air pads before delivery with the simulator are presented in Figure 10.

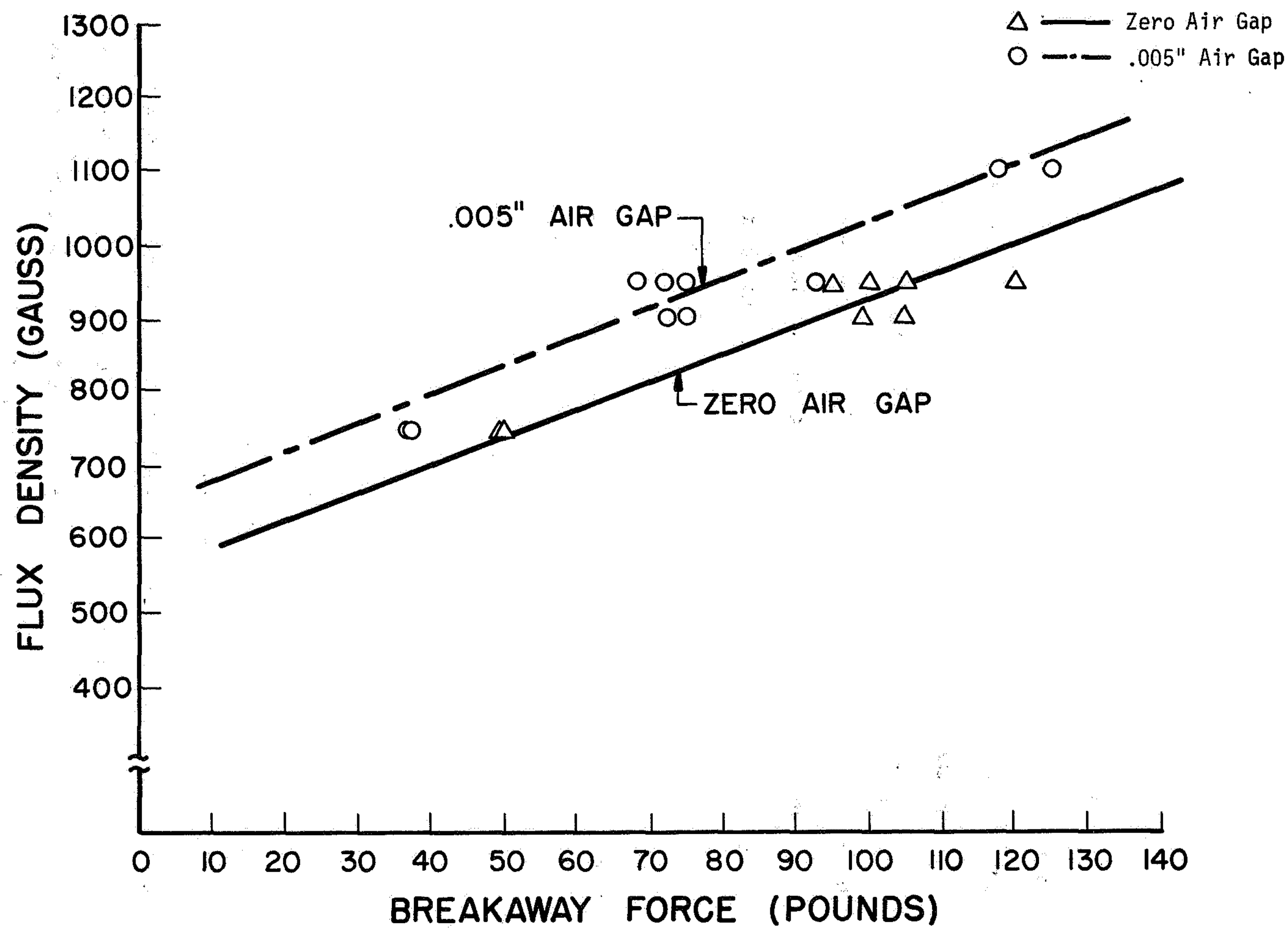

Figure 9 Breakaway Force vs. Magnetization Level for Magnetic Air Pads;
a) Zero Air Gap; b) With 0.005" Plastic Film.

Magnet Test

Arm and body support magnet pads were tested on a 3/8" thk. C. R. stl. plate with a 005" plastic film air gap, and with zero air gap.

Test Results

Magnet	Breakaway Load-005" Gap	Breakaway Load-Zero Gap
1. (Arm)	37 Lbs.	50 Lbs.
2. (Arm)	38 Lbs.	50 Lbs.
3. (Body)	93 Lbs.	120 Lbs.
4. (Body)	72 Lbs.	100 Lbs.
5. (Body)	75 Lbs.	105 Lbs.
6. (Body)	72 Lbs.	99 Lbs.
7. (Body)	75 Lbs.	105 Lbs.
8. (Body)	68 Lbs.	95 Lbs.

Figure 10 Breakaway Force as Measured for Each of the Magnetic Air Pads

The magnetic air pads are intended to operate at a pressure of 80 to 90 pounds per square inch. The equivalent of a 1/8 inch inner diameter hose must be provided to each pad to ensure that this pressure appears at the magnetic air pads under full flow conditions. It is suggested that air be distributed to each magnetic air pad from a central manifold located near the pad cluster. The air feed line to the manifold should hang straight down as far as possible so that a minimum of restraint is added to the cluster assembly.

It is essential that the overhead steel ceiling be as smooth as possible. The simulator built by John L. Fuller and Associates was shipped from Case Western Reserve University with a 4 ft. by 6 ft. steel ceiling made from hot rolled steel. Some trouble was experienced with "high spots" on this ceiling and it was necessary to smooth the ceiling by means of grinding and sanding for good operation. It is recommended that any new ceiling built for the system be constructed from cold rolled steel with as smooth a surface as possible. Care must be taken to avoid local irregularities caused by welding or forced assembly.

4.0 SYSTEM PERFORMANCE

4.1 Degrees of Freedom

The simulator has 6 degrees of freedom, some of which are restricted. Movement along the subject's X and Y axis are generally unrestricted. However, the minimal drag of the air supply and safety cables of the prototype limited the freedom of movement slightly along the X and Y axes. The dynamic characteristics of the overhead support devices (magnetic air pads and B-motors) were experimentally determined to be acceptable. They followed the segmented unit of the body, they were negating well and no annoying oscillation occurred at the end of a movement. It must be noted that the movements of magnetic air pads and motors relative to the negated units were observed while using the relatively small (4 ft. by 6 ft.) ceiling of the prototype, and though it was felt that the characteristics would hold for a large ceiling, this could not be experimentally verified.

Movement along the subject's Z axis (up and down) is relatively unrestricted, and though the B-motors have some measureable hysteresis, none was apparent to the test subjects.

Rotation around the subject's X, Y, and Z axes is unrestricted except as follows. Rotation around the X axis (roll) is limited for all practical purposes to 180 degrees. Rotation around the Y axis (pitch) is limited to 105 degrees. Rotation around the Z axis is unlimited except for the winding up of air lines and safety cables of the arm-force units which occurred when rotation of more than 360 degrees was made on the prototype.

It was felt that the above limited degrees of rotation, while somewhat severe in two cases (rotation around the X and Y axes) did allow the subject to experience unencumbered freedom of movement for what was presumed would be normal lunar gravity movements and actions.

4.2 Gross and Semi-Gross Activities

The 16 mm film delivered with this report best illustrates the kinds of activities that can be performed by a subject in the simulator.

Controlled gross activities which the subject can easily execute, some of which are illustrated in photographs, are as follows:

1. Standing (Figures 11 and 12), turning, bending backward (Figure 13);
2. Walking, running, loping, jumping;
3. Assuming a sitting position (Figure 14);
4. Assuming a crawling position (Figure 15) - hands and knees on floor;
5. Assuming a prone position (Figure 16);
6. Assuming a side-lying position (Figure 17);
7. Assuming a standing spread-eagle position (Figure 18).

In the loping and jumping exercises, the subject could rotate backward and/or to the side sufficiently to give him an indication that he had lost his balance in that direction. Most subjects used their arms to maintain their balance in the jumping situation (see film). It must be noted that the magnetic air bearings came loose from the ceiling several times during exaggerated exercises (i.e., maximum jump combined with a turn and fall to the floor). This was in part due to the largeness of the air gap (lowered gauss rating of the magnets), which was in turn necessitated by the surface roughness and undulating features of the hot rolled plate ceiling which was used on the prototype. Presumably, a better ceiling surface would allow the gauss setting for the magnets to be considerably higher.

The extent to which complex movements (i.e., combination of several gross activities) can be achieved is best illustrated by the film.

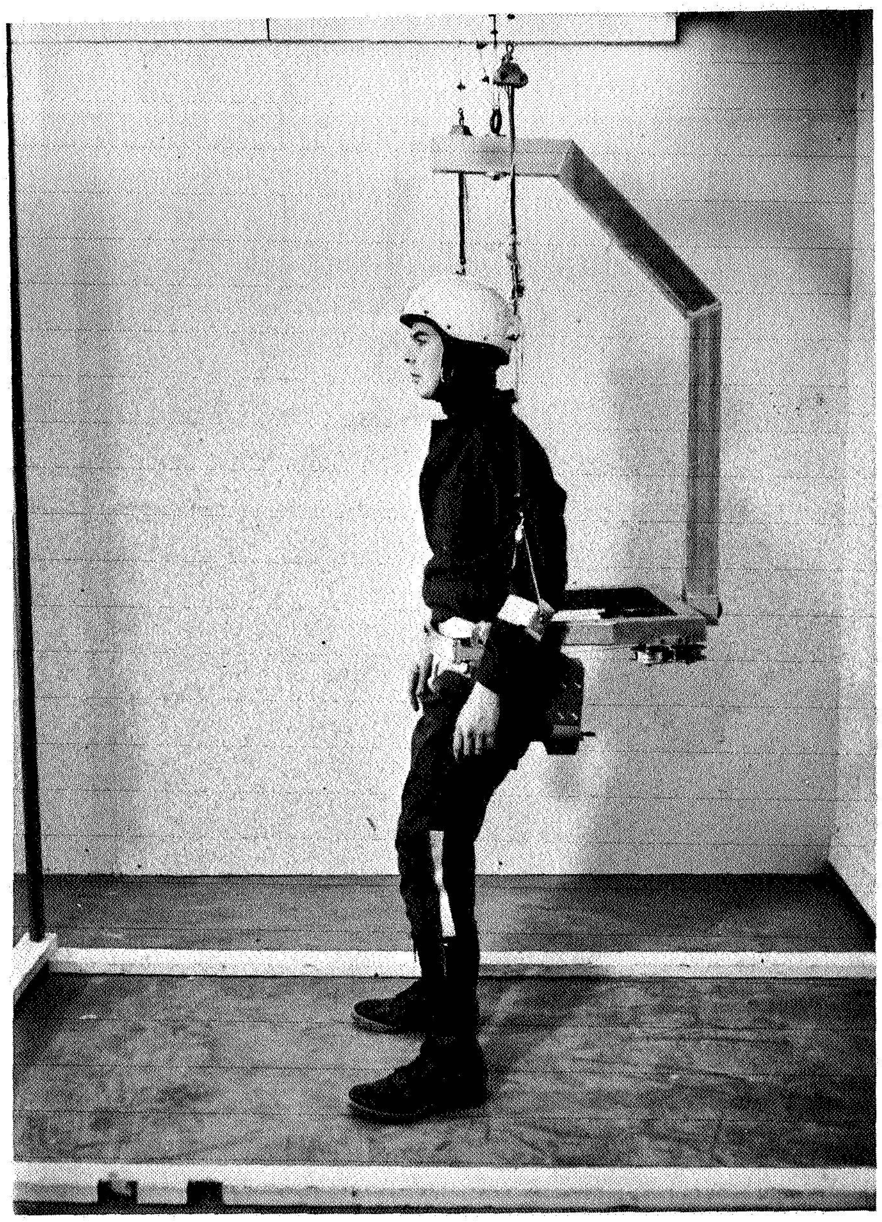

Figure 11 Side View Photo of
Subject Standing

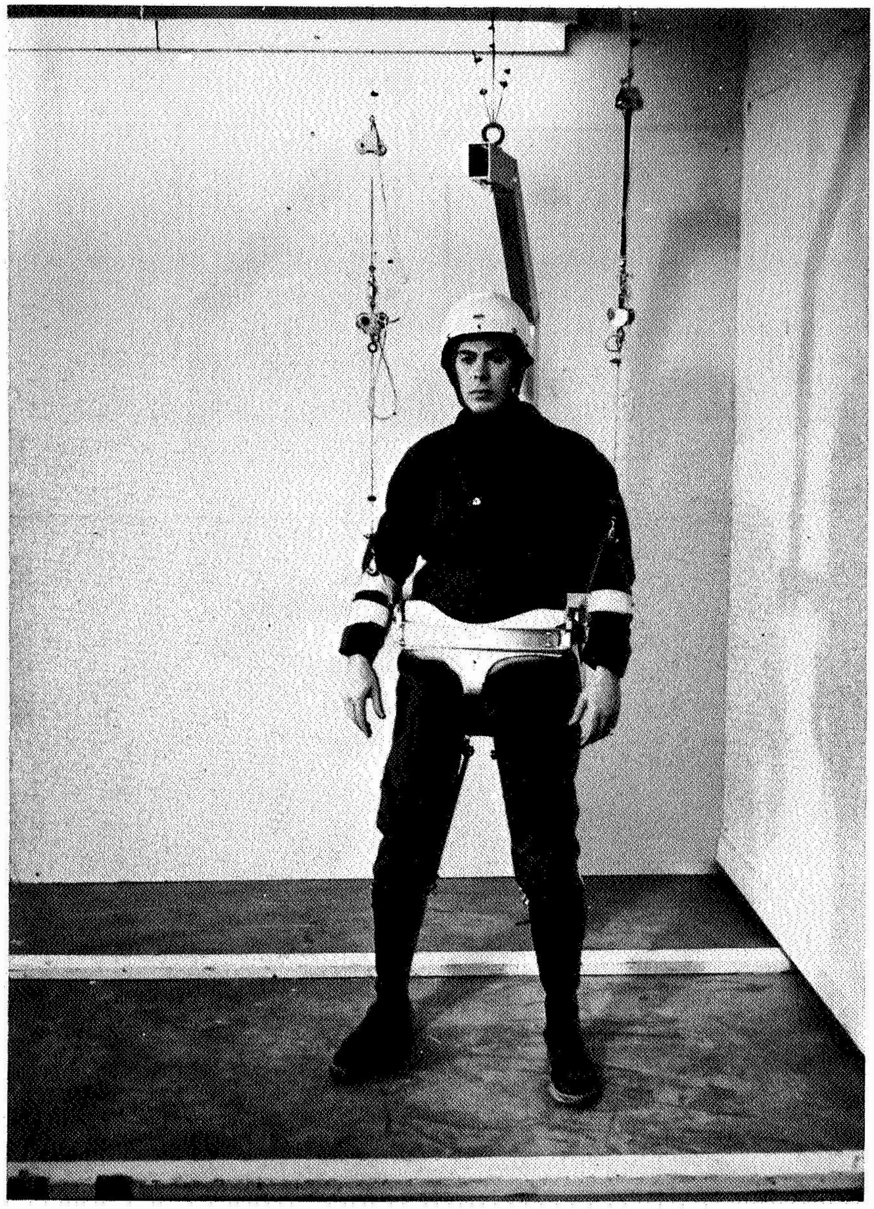

Figure 12 Front View Photo of Subject Standing

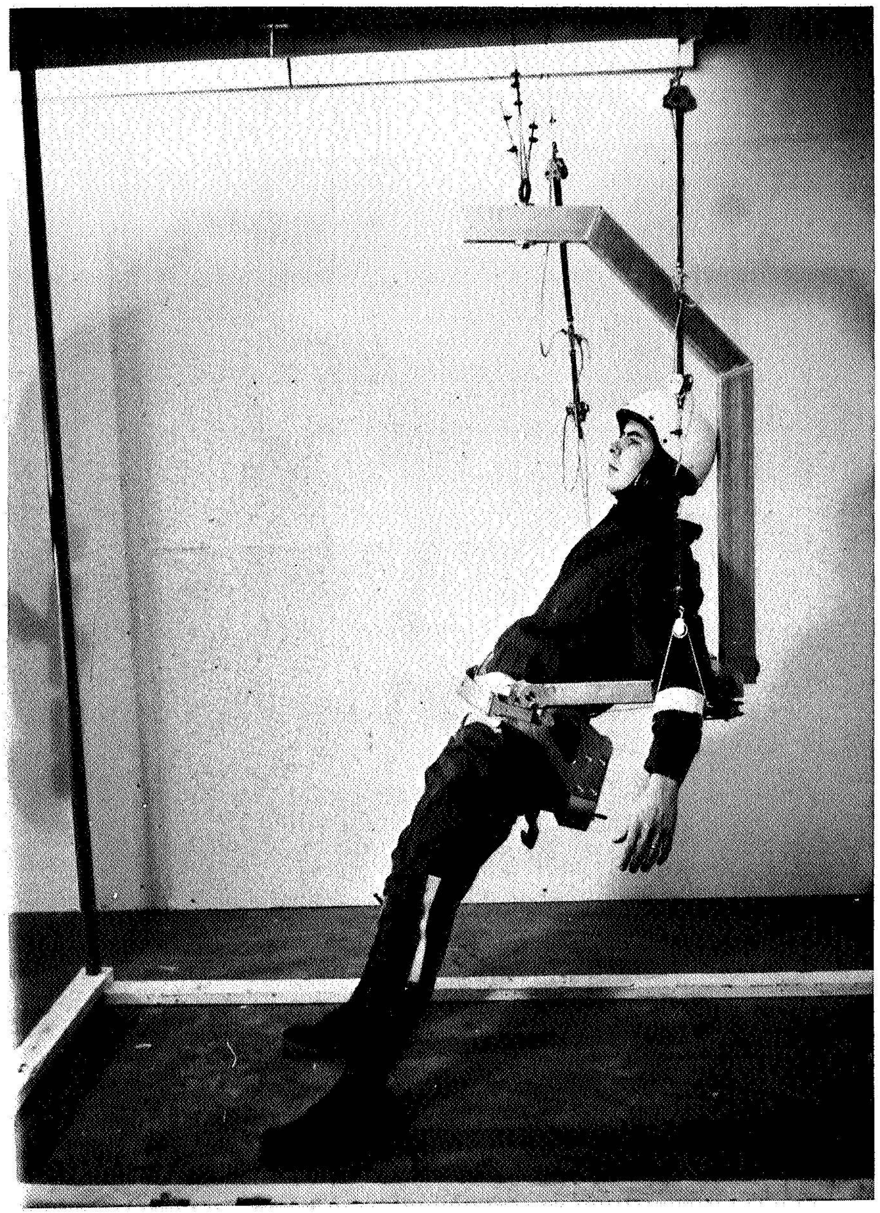

Figure 13 Photo of Subject Bending
Backward

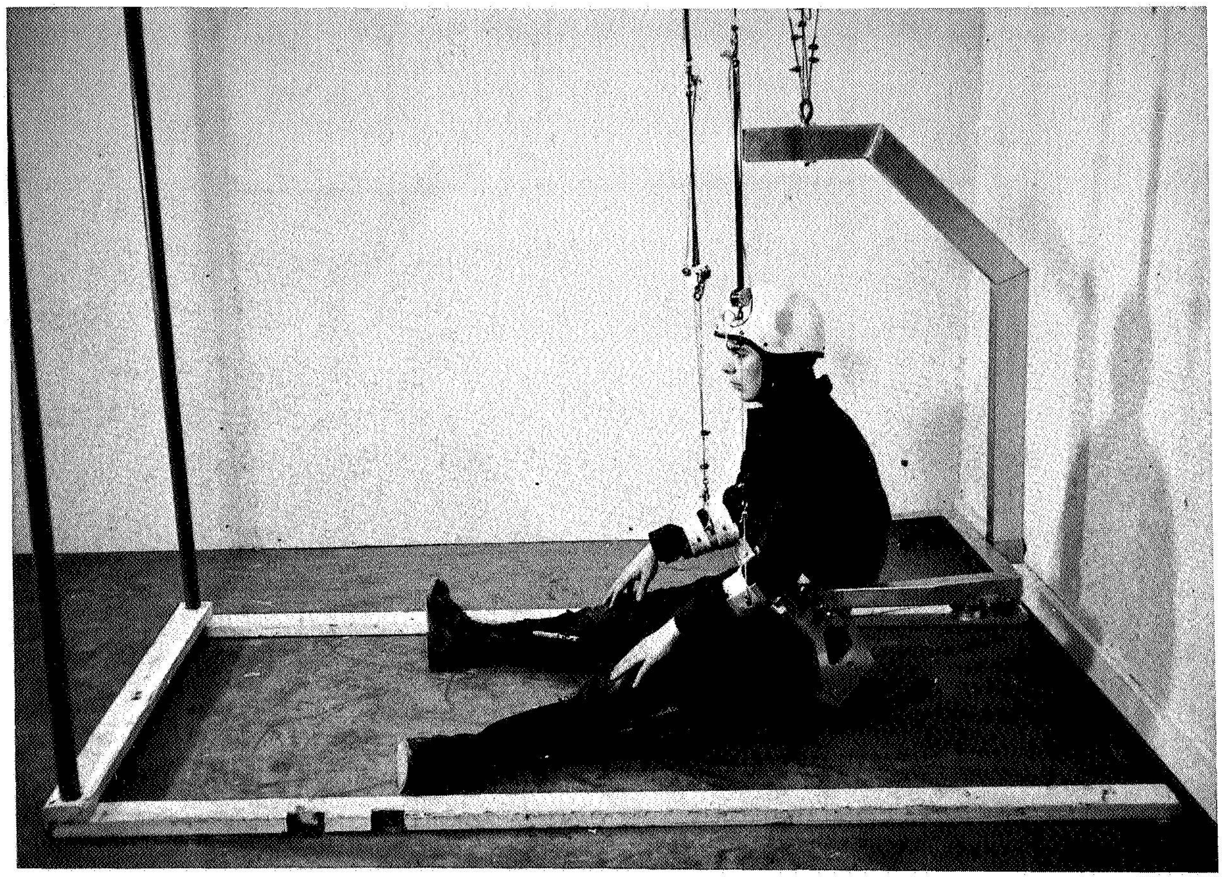

Figure 14 Photo of Subject Assuming
Sitting Position

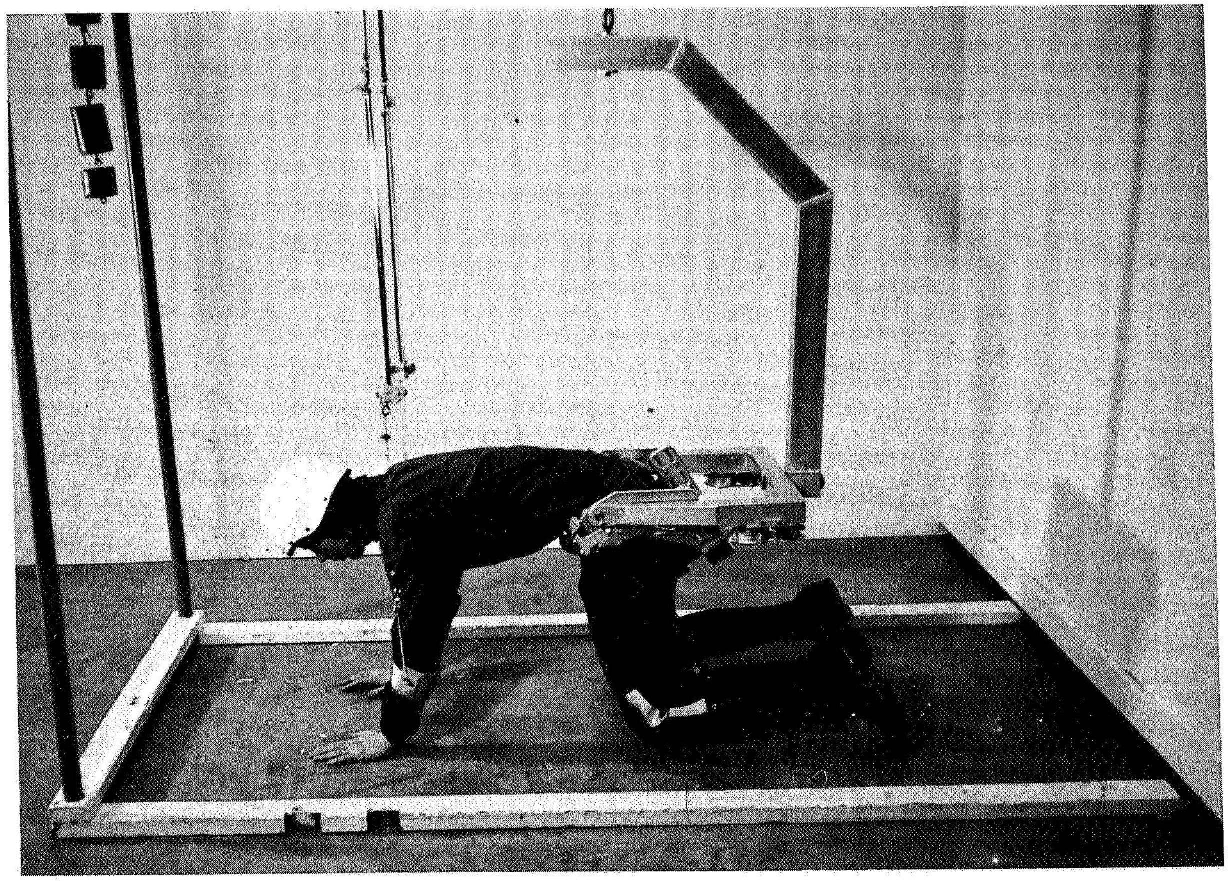

Figure 15 Photo of Subject Assuming A Crawling Position

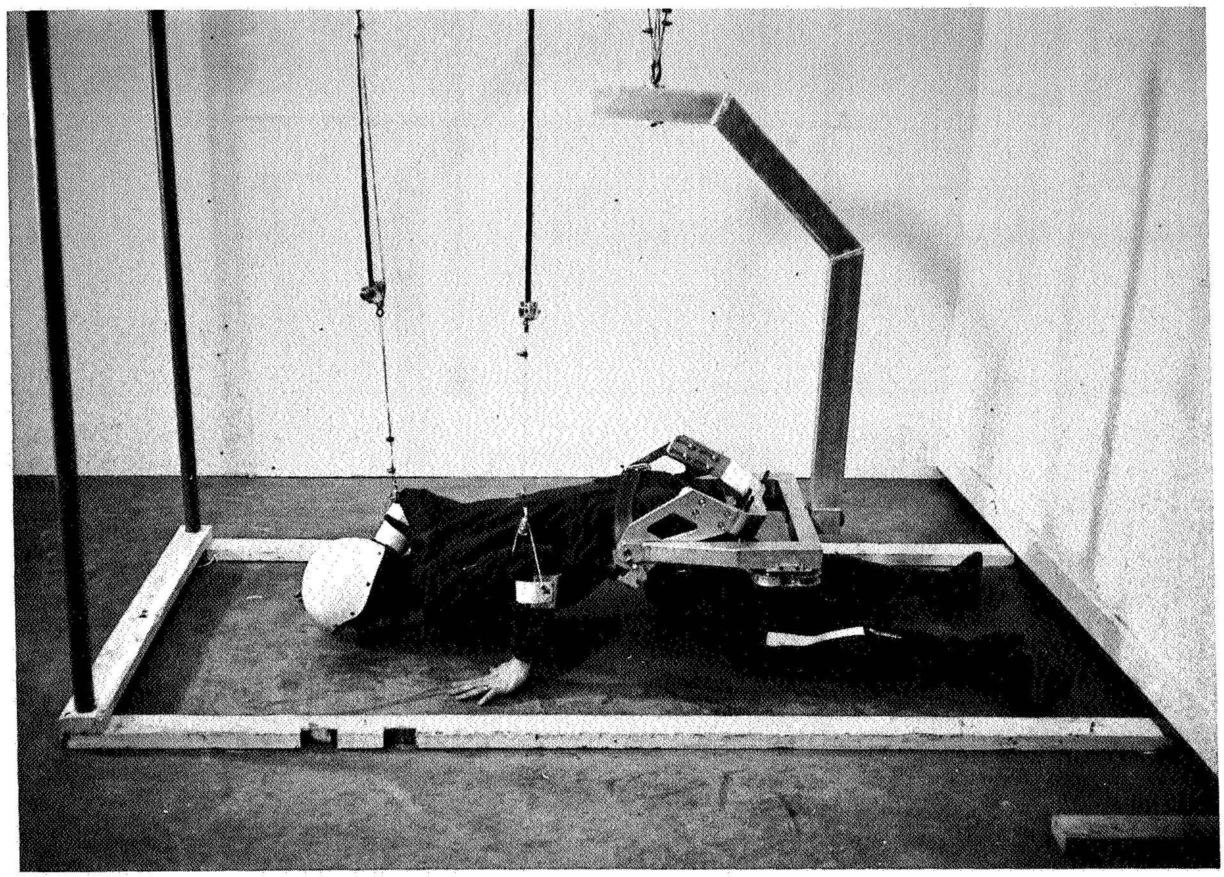

Figure 16 Photo of Subject Assuming Prone Position

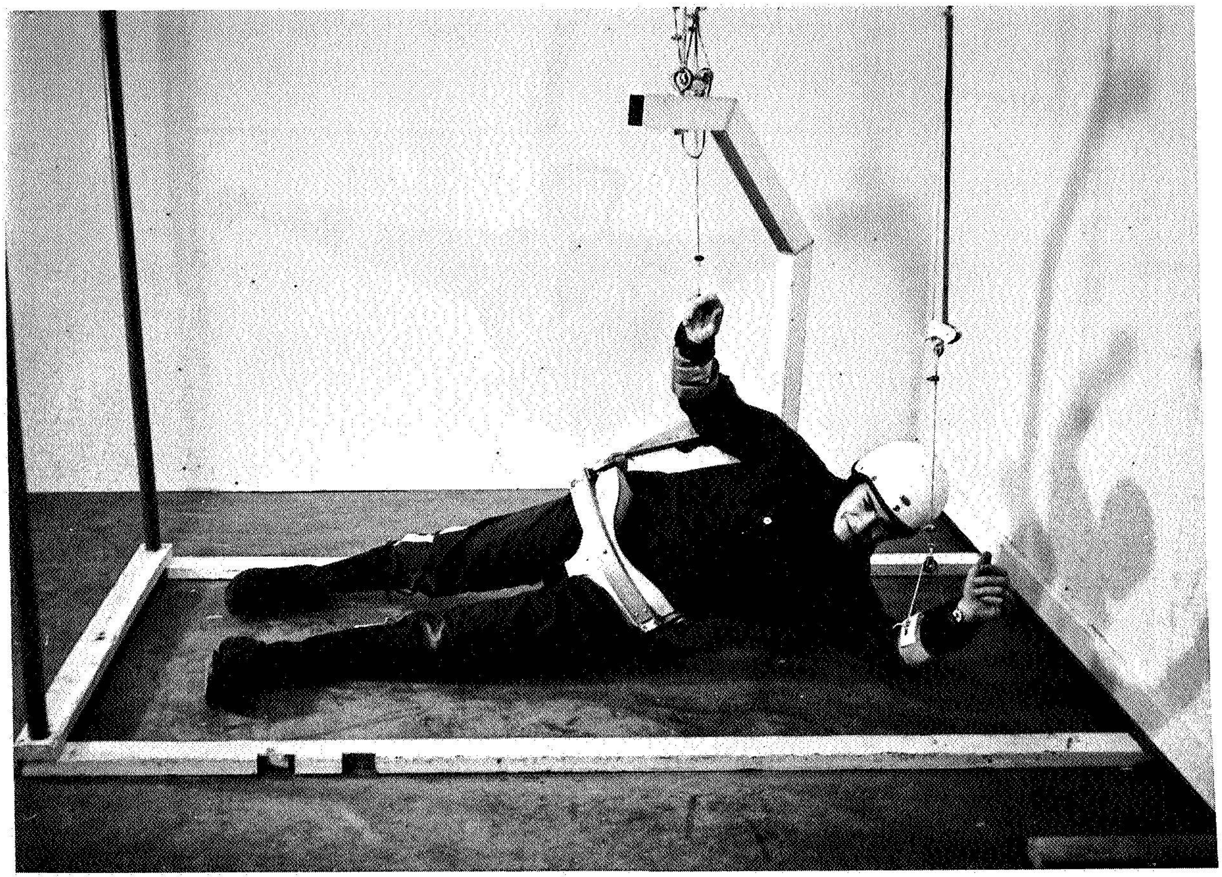

Figure 17 Photo of Subject Assuming a Side Lying Position

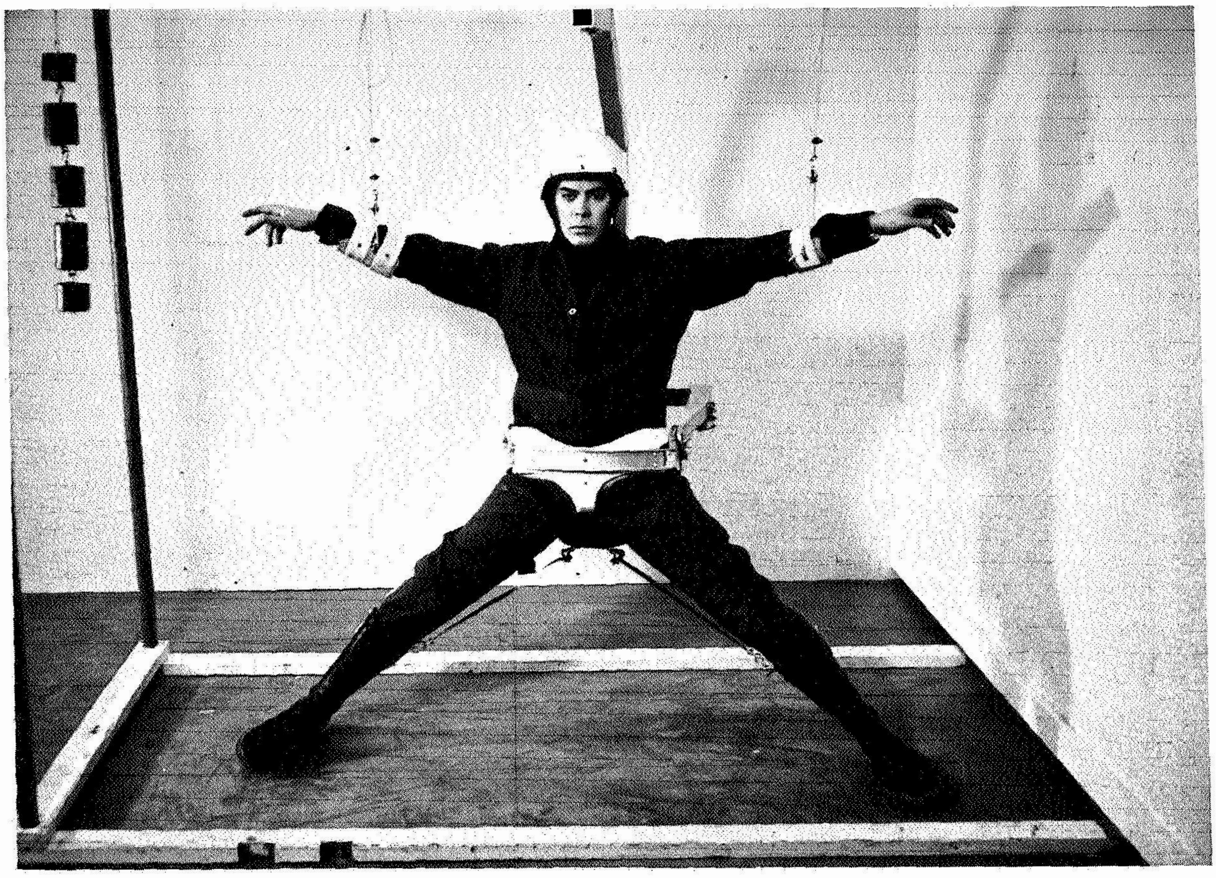

Figure 18 Photo of Subject Assuming a
Standing Spread Eagle Position

For semi-gross movements involving the leg and the arm, the leg has unrestricted normal movement and is generally well negated in normal walking and running positions. When the leg is positioned horizontally, as in crawling or prone positions, the negation of the leg is only partially 1/6 due to the angular vectors involved. The method used on the simulator which allowed for this condition was considered considerably better than the next best alternative which had leg negation going directly to ceiling-mounted B-motors. In the direct ceiling method, the leg support cable interfered excessively with arm movement and the one point mounting on the leg harness tended to pull the leg outward to the side.

The semi-gross movements of the arm are well negated in all positions and the arm is free to rotate completely about the shoulder joint. The only cable interference occurs when the subject might wrap his arms tightly about his upper torso or otherwise execute a similar extreme arm-crossing maneuver.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546